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TITLE A LOW-IMPEDANCE, 2.8-MHz, PULSED BUNCHING SYSTEM FOR THE LOS ALAMOS PROTON STORAGE RING

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A LOW-IMPEDANCE, 2.8-MHz, PULSED BUNCHING SYSTEM FOR THE LOS ALAMOS PROTON STORAGE RING*

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Summary

The Proton Storage Ring[1] (PSR) now under construction at Los Alamos National Laboratory is a device designed to accept a proton beam from the 800-MeV linear accelerator (LAMPF) and accumulate the protons to provide short, extremely high intensity bursts that drive a high-flux pulsed-neutron source. These bunches, which circulate at a 2.8-MHz frequency, are longitudinally confined by an rf electric field produced at that frequency by a ferrite-loaded coaxial quarter-wave resonator driven by a unique low-impedance rf amplifier. The buncher develops a 14-kV peak amplitude across the resonator gap and is energized in 3 ms-long pulses at rates up to 24 Hz. A principal design challenge exists because of high circulating beam currents (up to 45 A) that would, in a system driven by a conventional high-impedance amplifier, produce an induced voltage phased to interfere with the bunching action and much higher than that of the rf drive. The chosen solution is to feed the cavity from a low-output impedance amplifier whose final stages operate in Class A with a push-pull common-anode configuration. With this approach, similar to the rf system proposed for the colliding-beam accelerator (now cancelled) at BNL,[2] we can achieve an effective system impedance of about 25 Ω and can limit beam-induced effects to an acceptable level. This paper discusses the design of the cavity and amplifier and reports results from preliminary tests.

Introduction

The 90.2-m-circumference storage ring consists of a set of electromagnets that radially confines the protons and forces them to travel an approximately circular path. The period of rotation at 800 MeV is 360 ns, corresponding to a 2.795-MHz revolution frequency. During accumulation, a 270-ns-long burst of beam is injected into the ring each revolution; the timing is adjusted so that each burst stacks on top of those previously stored. A 90-ns gap is left open to allow for the finite rise time of a pulsed deflector magnet that eventually ejects the beam from the ring. Up to 2100 such bursts or bunches of protons, each containing about 2.6×10^{10} protons, are injected into the ring, reaching 5.2×10^{13} at the end of the accumulation cycle. The entire injection process is completed in ~750 µs, at which time pulsed magnets are energized to force the stored bunch out of the ring and to the neutron production target.

During the stacking operation, the single proton bunch must be confined longitudinally to maintain the extraction hole. This confinement is accomplished by an rf electric field applied across a gap in the metal vacuum chamber that, at full beam intensity, must reach a peak amplitude of 14 kV. To achieve confinement, one must decelerate protons arriving early at the bunching gap and accelerate late arrivals. This process requires a time-dependent electric field synchronized with the revolution period of the circulating beam. In its simplest form, the bunching system produces a 2.8-MHz sinusoidally varying voltage reaching 14 kV peak across the bunching gap and phased so that it passes through zero as the bunch center passes the gap. A more ideal bunching waveform would be a linear ramp; provisions have been made to approach this ideal shape by adding an appropriate amount of second- and third-harmonic components to the fundamental sinusoidal waveform.

A plan view of the PSR is included for general reference (see Fig. 1). The 2.8-MHz buncher gap is located in the lower left sector of the ring. The plan view also shows another set of bunchers that operates at a much higher frequency (503 MHz). In another mode of PSR operation, the 2.8-MHz buncher is turned off and this 503-MHz system is turned on instead, confining a set of very narrow bunches (1 ns wide). The high-frequency buncher operates at the 180th harmonic of the ring's fundamental revolution frequency; its significant design features have been described elsewhere.[3]

Beam Loading

The major feature of the bunching system described here is the use of a common-anode-configured amplifier to provide a low impedance across the bunching gap (tens of ohms). This feature is needed to reduce the effects of beam loading. A bunch containing 5×10^{13} protons revolving in the PSR every 360 ns represents an average current of 22 A. Furthermore, because the longitudinal proton density distribution

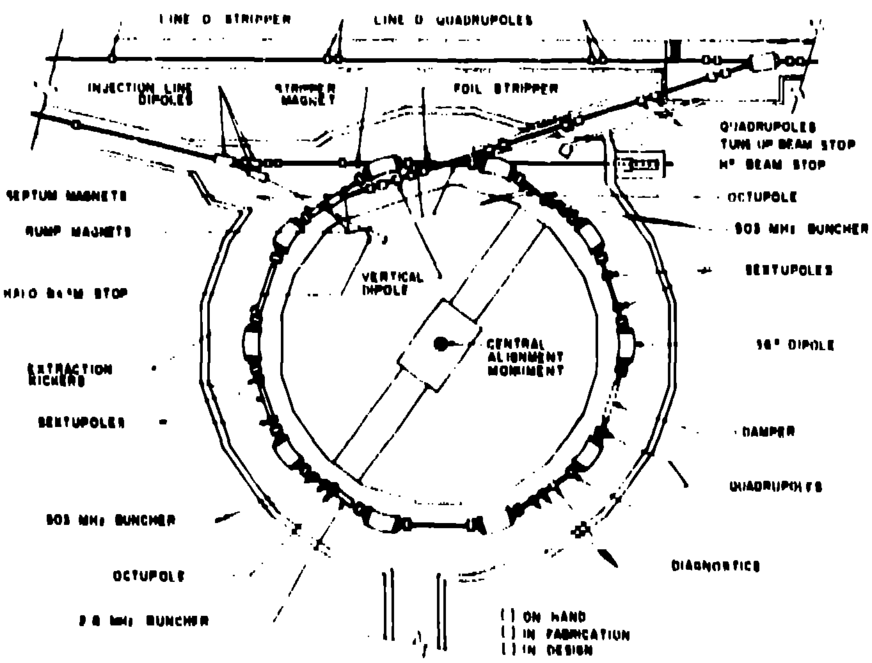

Fig. 1. Plan view of storage ring.

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is approximately parabolic, the peak current may exceed 45 A.

An image current travels along the inner surface of the metal vacuum chamber, along with the beam. When the image current encounters the bunching gap, it must cross it. Assuming a 4000-Ω shunt impedance, characteristic of the buncher cavity structure, the image current will induce a peak voltage of 88 000 V at the buncher gap. The beam current, and thus the image current, is 90° out of phase with the voltage required to provide bunching action. Figure 2 is a vector diagram showing the resulting voltage, which has a large component phased to decelerate the beam--an undesirable result.

The shunt impedance conventionally presented to beam-image current by the buncher structure can be represented by a parallel R,L,C resonant circuit. The structure is generally designed to provide a reasonably high impedance across which the power amplifier can develop the desired bunching voltage without excessive power requirements. It is possible to select the components of this circuit so that the beam current cancels a reactive current component. The resulting gap voltage will then be properly phased for bunching without deceleration. Figure 3 demonstrates this concept, which is equivalent to detuning the cavity. However, in our case the beam intensity (and thus the induced voltage) varies as a function of time (as injection proceeds) as does the desired bunching voltage. An active feedback system is thus required to implement this method of beam-loading control for the PSR. Because of the very large detuning angle required at the highest current levels, this method is complicated, subject to instability, and calls for a high-power tuning modulator.

Low-Impedance Driver

If the driving current source of Fig. 3 were replaced by a voltage source, the beam-image current would pass through it without inducing any voltage. This idea is the essence of the method selected to resolve beam-loading problems in the PSR 2.8-MHz bunching system. The amplifier, a common-anode-configured device capable of passing the peak beam current, acts as a voltage source in series with a 25-Ω impedance, mostly resistive. This low impedance allows the beam-image current to induce a maximum of ~500 V across the gap. Because the required maximum bunching voltage is 14 kV, the resulting phase error is only 2.0° and is within PSR requirements. No additional compensation by cavity detuning is required. With this driver configuration in parallel with the buncher gap, the beam sees the resulting network impedance as essentially the 25-Ω amplifier output resistance and not the 4000-Ω shunt impedance of the buncher cavity alone.

Cavity Structure

Figure 4 shows the physical details of the structure used to develop the desired bunching voltage. The structure is a pair of coaxial quarter-wavelength transmission lines shorted at the ends and arranged in a balanced configuration. The lines are loaded with 40 moderate-permeability ferrite rings ($\mu \cong 400$), to reduce the physical size of the structure. These lines are somewhat electrically shorter than a quarter-wavelength, thus shifting the periodic resonances off the beam-revolution harmonics. Resonance at 2.8 MHz is accomplished by capacitively terminating the open ends of the lines. Magnetic-bias field windings are arranged in a series-opposing configuration and powered by a dc current to magnetize the ferrite cores and produce the desired resonant frequency by adjusting the ferrite permeability. At 2.8 MHz, with the cavity adjusted for resonance, the structure exhibits a 4000-Ω shunt impedance and requires 49-kW peak power to produce the 14-kV peak bunching voltage.

Amplifier System

The buncher amplifier is required to provide a 1-ms-long burst of 2.8-MHz rf voltage at a 24-Hz repetition rate. This voltage must be phased to provide a zero crossing when the centroid of the beam-bunch charge passes the bunching gap. The rf voltage must be amplitude modulated in proportion to the accumulated beam intensity. A significant fraction of second- and third-harmonic components will be added to the fundamental to produce an approximately sawtoothed (ramp) waveform. The amplifier should present a low impedance across the bunching gap.

Table I gives a detailed listing of the buncher system parameters and Fig. 5 is a block diagram of the system that has been designed to meet these parameters. The amplifier is a broad-band chain consisting of a pair of common-anode-configured Amperex 5918 industrial triodes, which form the final amplifier stage and common-cathode configured Eimac 4 CW 25000 power-tetrode driver/predriver stages. The final stage

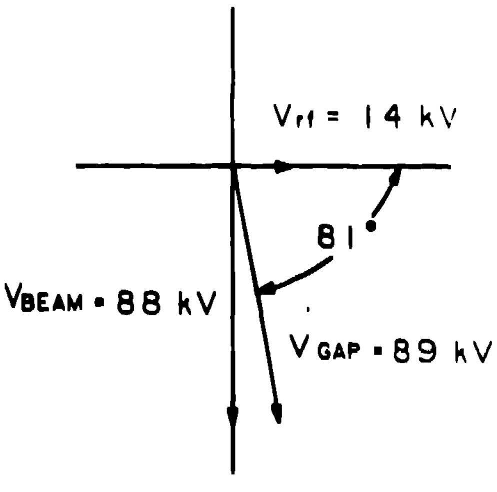

Fig. 2. Vector diagram. Beam-induced voltage at 5 x 10[13] protons.

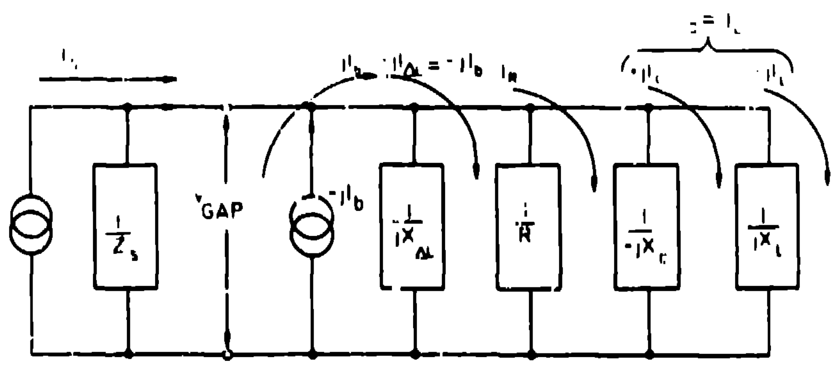

Fig. 3. Equivalent circuit demonstrating the addition of a reactive element ΔL to compensate for beam loading. The added reactive element ΔL is selected so that it passes the entire beam-current component.

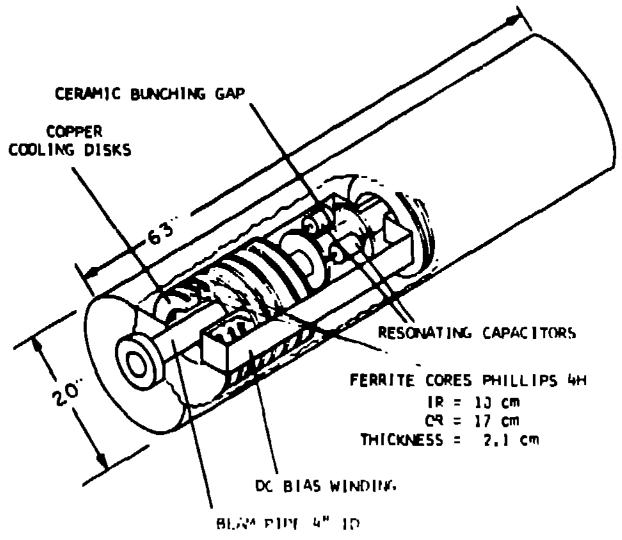

Fig. 4. Bunching cavity physical details.

operates push-pull Class A. The driver and predriver stages operate Class ABI. All stages are held at cut-off, then are brought into conduction during the beam cycle by pulsing the tube grid bias. Capacitor banks provide the necessary dc energy during the beam cycle, and current-regulated high-voltage supplies recharge these capacitors between cycles. Fast-crowbar protection circuits are included to prevent damage to tubes and other components during a fault condition.

Figure 6 shows the calculated output impedance of a common-anode, Class A, single-ended amplifier stage using an Amperex 8918A industrial triode. The calculation takes into account interelectrode capacitances and the input transformer and terminating resistors, representing half our actual amplifier--one would expect twice this impedance across the bunching gap. The model has not accounted for tube inductance and assumes perfect anode bypassing. In reality, the impedance presented across the gap will be somewhat higher than this simple model predicts.

Figure 7 is a circuit diagram of our 8918 final-amplifier stage. The heaters are fed from low-capacity (12-pF) wide-spaced filament transformers, allowing the entire secondary winding to swing with the output voltage. The filament leads are bypassed near the tube by balanced capacitor decks, and a broad copper strap connected between the capacitor decks forms the output lead. Anode bypassing is accomplished with broad plates both above and below a ground plane and insulated with Kapton sheets. An array of transmitting mica capacitors of various values connects to the ends of these plates. The broad plates form an effective high-frequency distributed capacitor and provide a means of connecting the large lumped elements.

Each triode is housed in its own enclosure (Fig. 8). These enclosures are set on heavy-duty slides and input/output connections are accomplished with sliding contact blocks. Quick-connect fittings located on the rear of the modules are employed for cooling-water, ac power and high voltage. Components are arranged within the modules in a symmetric fashion, allowing a single spare module to be converted easily from a right-hand unit to a left-hand module.

TABLE I

BUNCHER SYSTEM PARAMETERS

General:	
Frequency	2.795139 MHz
Harmonic number	1
Maximum bunching voltage	14 kV, peak
Stable phase angle	0°
Cavity:	
Number of cavities	1
Gaps per cavity	1
Gap impedance:	
Entire system	25 Ω
Cavity only	4000 Ω
Inductance:	
Nominal	16 μH
Range	8-30 μH
Resonating capacity:	
Total	200 pf
Distributed and stray	75 pf
Fixed	125 pf
Tuning:	
Frequency range	2-4 MHz
Bias winding turns	1
Nominal bias current	170 A
Bias current range	0-500 A
The rf power dissipated in ferrite	1.5 kW @ 12 Hz 3.0 kW @ 24 Hz
Amplifier:	
Type	Common anode
Configuration	Push-Pull
Class of operation	A: gated
Maximum duty cycle	7%
Maximum rf pulse length	3 ms at 14 kV peak
The rms input power	23 kW @ 12 Hz 46 kW @ 24 Hz
Power tube	Amperex 8918
The dc Supply:	
Type	Current and voltage-regulated charging supply and capacitor bank
Voltage	15 kV maximum
Stored energy	32 kJ maximum
Protection:	
High voltage	Fast crowbar Spark gaps at tube elements
Cooling	Cavity overtemperature Water pressure relief Water flow
Other	Poor cavity vacuum

Pearson Model 1010 current transformers are included within the 8918 modules as a diagnostic to monitor tube current. The input transformer and terminating resistors, both water-cooled, are also mounted on slides. This input module is not removable, but all components are readily accessible with the module fully extended.

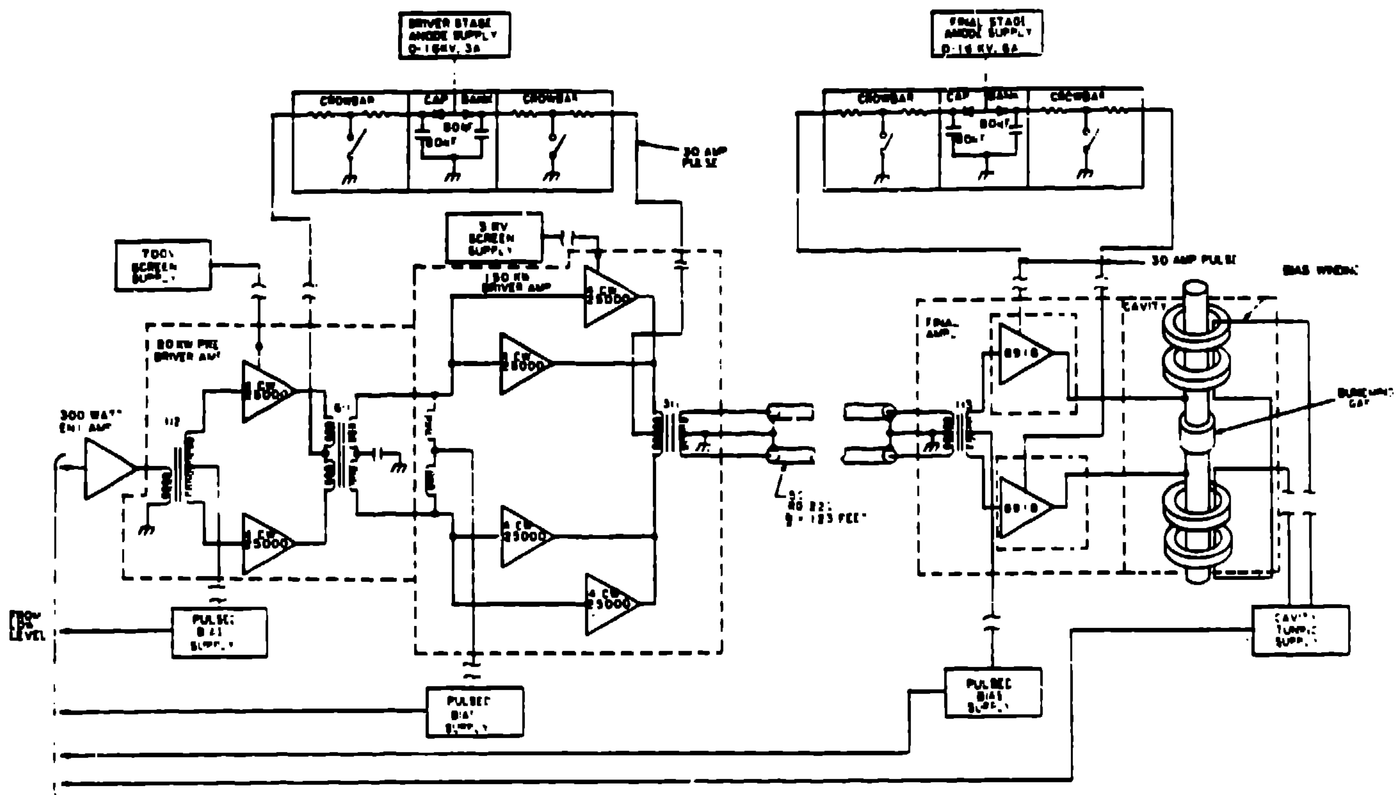

Fig. 5. PSR 2.8-MHz buncher system block diagram.

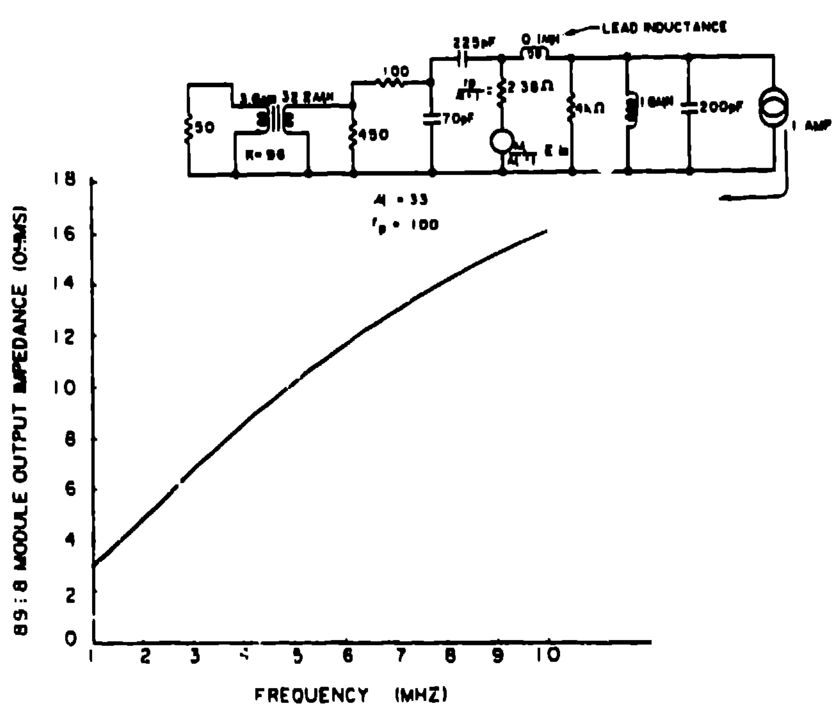

Fig. 6. Calculated output impedance for a single 8918 module.

Driver Stages

Common-anode amplifiers are notoriously difficult to drive at high frequencies because they have a voltage gain less than unity. Each 8918 module must be driven with a 7000-V peak signal and its input impedance at 2.8 MHz, primarily the 70-pF grid-to-plate capacitance, is about 800-Ω capacitive. Because broad-band operation is desired, to allow the addition of second- and third-harmonic components, 450-Ω input terminating resistors are shunted across the grid to plate capacitance. The driver stage must provide about 18-A peak to this parallel network for each 8918 module. The driver stage consists of four Eimac 4 CW 25000 power tetrodes operated in a parallel push-pull configuration. The tubes are operated at 10-kV anode voltage and with 2500- to 3000-V screen potential. The driver stage is transformer coupled to a pair of 50-Ω half-wavelength transmission lines that feed the input transformer of the final stage. A predriver stage consisting of a pair of 4 CW 25000 tetrodes provides grid input to the driver stage. An ENI A300 solid-state amplifier feeds the predriver.

Programmable Grid Supply

During the time between PSR beam pulses, about 40 ms, all amplifier stages are held in cutoff by programmable grid supplies. These solid-state supplies can provide up to 1500-V cutoff bias into 10-kΩ loads and can provide a positive-going 1000-V pulse into a dynamic load of 200 Ω. A Static Induction Transistor (SIT), Tokin model 2 SK 183V, is operated in a linear mode to allow for ramped bias control or for any other desired program function. Gate drive for the SIT is obtained from a negatively offset RCA-HC 2500 power operational amplifier. Feedback for the RCA-HC 2500 is derived

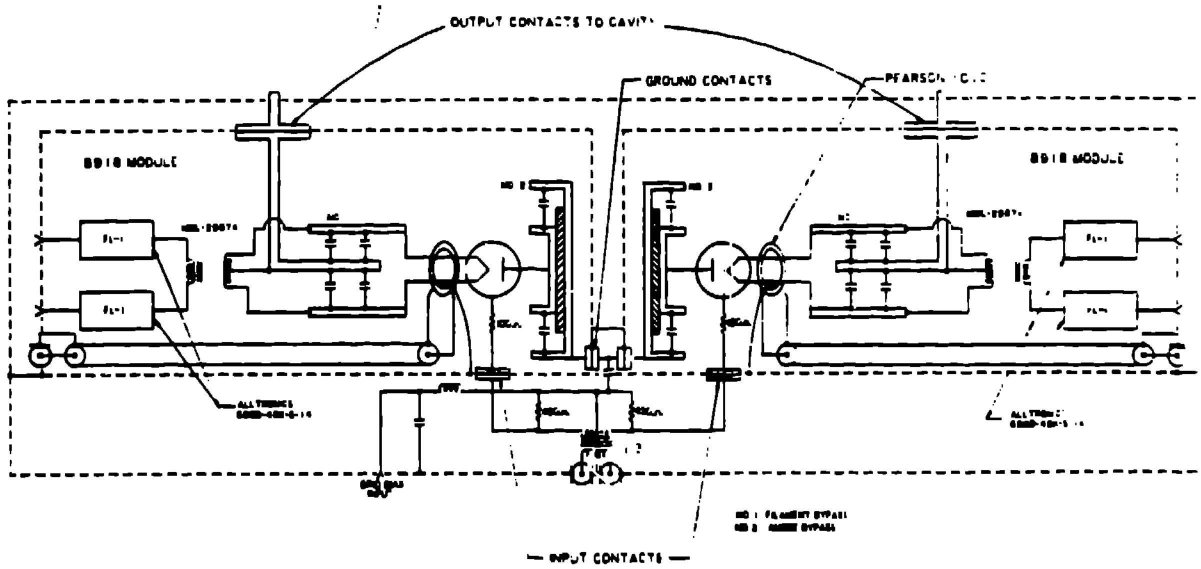

Fig. 7. Final amplifier stage circuit diagram.

Fig. 8. The 8918 module.

from a 10-Ω resistor in the SIT source circuit. Both the SIT and the RCA-HC 2500 float at the cutoff bias voltage. An Analog Devices AD-289L isolation amplifier provides the 1500-V input signal isolation.

Results

The 2.8-MHz PSR buncher system is now about 70% complete, with one 8918 module; all power supplies, crowbars, and capacitor banks; the driver stage; and the bunching cavity itself on hand. A single, 8918 final-amplifier module has been operated into the bunching cavity at 12-kV peak voltage across the gap. During final stage testing, the cavity was detuned to appear either capacitive or inductive with no indication of stability difficulties. The amplifier output impedance is in the tens of ohms at 2.8 MHz, but a more detailed measurement of the actual impedance that will be seen by the beam awaits completion of the second 8918 module.

Acknowledgment

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